

# The effect of advection at luminosities close to Eddington: The ULX in M31

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## ABSTRACT

The transient, ultra-luminous X-ray source CXOM31 J004253.1+411422 in the Andromeda galaxy is most likely a 10 solar mass black hole, with super-Eddington luminosity at its peak. The *XMM-Newton* spectra taken during the decline then track luminosities of  $0.86 - 0.27 L_{\text{Edd}}$ . These spectra are all dominated by a hot disc component, which roughly follows a constant inner radius track in luminosity and temperature as the source declines. However, at the highest luminosity the disc structure should change due to advection of radiation through the disc. This advected flux can be partly released in the plunging region, with the remainder being advected below the event horizon. We use a fully relativistic disc model, SLIMBH, that includes these effects, and uses full radiative transfer through the photosphere based on TLUSTY. It also incorporates full relativistic photon ray-tracing from the proper location of the disc photosphere rather than the mid-plane as the disc is no longer geometrically thin. However, we find that these new models differ only very slightly from the non-advective (standard) BHSPEC even at the highest luminosities considered here. While both discs can fit the highest luminosity data, neither is a good fit to the *lower* luminosities. We speculate that this could be due to a decreasing fraction of magnetic pressure support with increasing luminosity, such as seen in models where the magnetic pressure saturates to some fraction of the gas rather than total (gas plus radiation) pressure.

**Key words:** accretion, accretion discs – X-rays: binaries, black hole.

## 1 INTRODUCTION

The most luminous objects in the Universe are powered by accretion of matter onto compact objects like neutron stars and black holes. The energy released depends on the mass and spin of the central black hole as well as the mass accretion rate through the disc, but there is a maximum luminosity for which gravity is able to exceed the outward pressure of radiation. Ultra-luminous X-ray sources (ULX) are defined as objects whose bolometric luminosity exceeds this Eddington limit for a  $\sim 10 M_{\odot}$  black hole ( $\sim 1.3 \times 10^{39} \text{ erg s}^{-1}$ ). These objects could be powered by normal (sub-Eddington) accretion onto intermediate mass black holes ( $M_{\text{BH}} \simeq 10^2 - 10^5 M_{\odot}$ ). However, there are theoretical problems concerning the formation of such objects (King et al. 2001), so these are unlikely to form the bulk of the ULX population. Instead, the majority of sources are probably *super*-Eddington accreting stellar mass black holes. Such flows come in two flavours, either exceeding the Eddington limit by powering strong outflows (Shakura & Sunyaev 1973; Lipunova 1999; Poutanen et al. 2007), or by advecting the radiation along with the flow (Polish doughnuts: Abramowicz et al. (1978); Jaroszynski et al. (1980);

slim discs: Abramowicz et al. (1988); Sądowski (2009)). These processes can occur together (Poutanen et al. 2007), as shown in recent numerical simulations of super-Eddington flows (Ohsuga et al. 2009; Ohsuga & Mineshige 2011). In all these cases, radiation is emitted at the local Eddington limit, so that the total source luminosity is  $L \sim L_{\text{Edd}}(1 + \ln M/M_{\text{Edd}})$ . Advective accretion discs that locally can exceed the Eddington limit and thus excite winds were proposed by Dotan & Shaviv (2011).

The BHSPEC models are the best current sub-Eddington accretion flow models for stellar mass black holes (Davis et al. 2005). These calculate the spectrum from full radiative transfer through a disc atmosphere for a Novikov-Thorne (general relativistic) emissivity, including ray tracing incorporating general and special relativistic effects. These were modified to include the effects of advection by Bursa et al. (2012, in preparation). Advection sweeps some of the emitted energy along with the flow as photons are trapped in the optically thick disc. However, these photons can be released again at lower radii as the material accelerates towards the black hole after the inner disc edge. Pressure forces can change the position of this inner edge from that expected from the innermost stable circular orbit, and increase the height of the photosphere as the disc is no longer flat. The resulting SLIMBH models were fit to spectra from the accreting black hole in LMC X-3. However, the differ-

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ences between BHSPEC and SLIMBH are not large here although this object reaches  $\sim 0.6L_{\text{Edd}}$  (Straub et al. 2011).

Here instead we fit these new models to the higher Eddington fraction flows seen in ULX. In particular, we use the XMM-Newton spectrum from the transient ULX CXOM31 J004253.1+411422 (hereafter M31 ULX-1). The advantage of this object is that it showed a steady exponential decline in luminosity in five XMM-Newton spectra from  $1.6 - 0.8 \times 10^{39} \text{ erg s}^{-1}$  after its discovery at  $5 \times 10^{39} \text{ erg s}^{-1}$  in Chandra imaging data. Such exponential decays with this time scale are well known from transient low mass X-ray binary black holes in our Galaxy, making it most probable that this ULX is also a  $10M_{\odot}$  black hole (Middleton et al. 2012; Kaur et al. 2012). This mass would then imply that the luminosity sampled by the XMM-Newton spectra corresponds to  $0.86 - 0.27L_{\text{Edd}}$ , considerably higher than seen in LMC X-3. Thus it provides an ideal testing ground for the slim disc models, especially as the Galactic absorption column is fairly low, allowing the broad band disc shape to be seen down to low energies.

The paper is structured as follows. The origin and analysis of our data is specified in section 2, the modelling of the ULX spectra is described in section 3 and the results are discussed in section 4.

## 2 X-RAY DATA: REDUCTION AND ANALYSIS

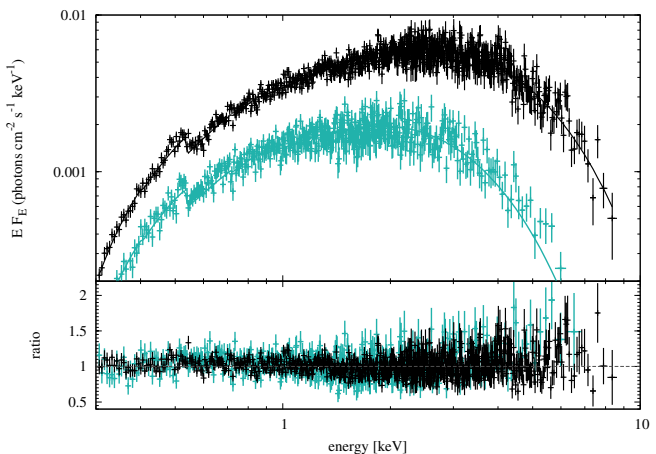
To ensure consistency, we followed the procedure of data reduction detailed in Middleton et al. (2012) and extracted the event files using *sas* v10 and filtered the products for standard patterns ( $\leq 12$  for MOS,  $\leq 4$  for PN) and flags ( $=0$  for spectral and timing products). The full field hard (10–15 keV) count rate was used to create good time intervals excluding contamination by soft proton flares (see Table 1 of Middleton et al. 2012). These were then used to extract spectral (including responses) and timing products from a circular, 35'' radius source, with background regions taken from the same chip, avoiding other sources in the field.

The first observation was slightly piled up (seen using the tool, *EPATPLOT*), so the inner 5'' centroid centred on the source was removed in the PN. The MOS is more affected by pileup, so was discarded for this observation.

## 3 MODELLING THERMAL ULX SPECTRA

For the trans-Eddington luminosity regime of ULX spectra the best available model to date is the relativistic slim disc, SLIMBH (Bursa et al. 2012, in preparation). It accounts for effects connected to high mass accretion rates such as advection of radiation, the relocation of the innermost stable circular orbit (ISCO) towards smaller radii and the proper, non-equatorial location of the disc photosphere (see Sądowski et al. 2011; Straub et al. 2011). For the vertical radiative transfer SLIMBH directly incorporates the TLUSTY grid of disc local annuli spectra (Hubeny & Lanz 1995) which are then integrated and ray-traced through the relativistic spacetime. It is thus constructed in the same manner as BHSPEC (Davis & Hubeny 2006). We note that the difference between the two models is the underlying accretion disc: While BHSPEC is based on a standard thin Novikov & Thorne (1973) disc, SLIMBH uses a slim disc (Sądowski 2009). A comparison of these two models offers valuable insight on the effect of advection (see section 3.1).

Middleton et al. (2012) fit the five XMM-Newton spectra of M31 ULX-1 simultaneously with *TBABS*  $\times$  *BHSPEC* using the neutral hydrogen column density  $N_H = 6.7 \times 10^{20} \text{ cm}^{-2}$  (after



**Figure 1.** X-ray spectra of M31 ULX-1, modelled with SLIMBH. Spectrum and data/model ratio for the highest ( $= 0.85L_{\text{Edd}}$ , black) and the lowest ( $= 0.27L_{\text{Edd}}$ , cyan) luminosity data are shown.

Dickey & Lockman 1990), distance  $D = 780$  kpc (Vilardell et al. 2010; Tanaka et al. 2010) and viscosity parameter  $\alpha = 0.01$ . With black hole mass fixed to the provisional value of  $M = 10M_{\odot}$  they derived best fit inclination of  $i = 30^{\circ}$  and dimensionless spin parameter  $a_* = 0.36^{+0.10}_{-0.11}$ . The fit is fairly good, with  $\chi^2_{\nu} = 3169.4/2801$ , though the spectra are significantly better fit with a *phenomenological* model of *TBABS*  $\times$  (*DISKPB*+*COMPTT*) ( $\chi^2_{\nu} = 2752.2/2777$ ).

We now replace the BHSPEC model with SLIMBH, again with  $\alpha = 0.01$ , to see if this can better reproduce the spectral shape, and give a *physical* model which fits the data as well as the phenomenological one. Advection should become increasingly important after  $L \sim 0.1L_{\text{Edd}}$  so the differences between BHSPEC and SLIMBH could be significant. We find that the more physical models do fit the data slightly better, but that the improvement is only small, with  $\chi^2_{\nu} = 3132.2/2801$  for the same resulting black hole spin (see Table 1).

A closer inspection of the spectral residuals shown in Middleton et al. (2012) explains this result. The residuals between BHSPEC and the data are largest at *lowest* luminosities, with the data being increasingly well fit by the non-advective disc models at higher luminosities. This is opposite to the behaviour expected if advection becomes increasingly important, limiting the impact of the spectral changes from SLIMBH. We explore the differences between BHSPEC, SLIMBH and the data in more detail below.

### 3.1 Effect of advection: The difference between SLIMBH and BHSPEC

Figure 2a shows the best fit model spectra of SLIMBH (red) and BHSPEC (blue). Their ratio (black/cyan) for identical mass ( $10M_{\odot}$ ), spin ( $a_* = 0.36$ ), inclination ( $30^{\circ}$ ) and luminosity ( $= 0.86/0.27L_{\text{Edd}}$ ) is presented in the top panel of Figure 2b. For the highest luminosity, the slim disc is very slightly softer below the peak as radiation is transported inwards at these radii rather than being emitted. Some fraction of this advected radiation can then be released below the ISCO, so there is additional radiation in the SLIMBH models at the highest energies i.e. above the peak. Thus the SLIMBH models are broader and not so peaked as the corresponding BHSPEC models, but the difference is less than a few per

**Table 1.** Slim disc model: best fitting spectral parameters

TBABS * SLIMBH					
Observation	1	2	3	4	5
$N_H$ [ $cm^{-2}$ ]			$6.7 \times 10^{20}$		
$M_{BH}$ [ $M_\odot$ ]			10		
$a_*$			$0.36^{+0.02}_{-0.02}$		
$L/L_{Edd}$	$0.855^{+0.008}_{-0.008}$	$0.593^{+0.006}_{-0.005}$	$0.428^{+0.006}_{-0.006}$	$0.336^{+0.004}_{-0.004}$	$0.271^{+0.004}_{-0.004}$
$\alpha$			0.01		
$i$ [ $^\circ$ ]			30		
$D$ [kpc]			780		
$\chi^2/dof$ ( $\chi^2_\nu$ )			3132.2/2801 (1.12)		

cent for  $0.86L_{Edd}$ . Advection only makes a more substantial difference to the emitted spectrum for super-Eddington luminosities, and there is even less difference between SLIMBH and BHSPEC at lower luminosities ( $0.27L_{Edd}$ ).

However, there is a significant change in how well the models describe the data. The green lines in Figure 2a show the best fit phenomenological DISKPBB+POWERLAW model for the highest/lowest luminosity dataset. The highest luminosity dataset is well described by either disc model. By contrast, the lower luminosity dataset is clearly broader than the corresponding BHSPEC and SLIMBH models. The discrepancies between physical and phenomenological models are illustrated in the bottom panel of Figure 2b where the model ratio SLIMBH vs DISKPBB+POWERLAW for the highest (black) and lowest (cyan) luminosity is given.

Thus, including advection does not change the conclusion of Middleton et al. (2012) that the data (especially at lower luminosity) are better fit by phenomenological two component models rather than our best current physical disc models. This shows that there is something missing from our best current disc models. We stress that the level is only 5-10 per cent, but this is significant given the quality of data now available. The missing physics is not advection, nor is it any of the other spectral distortions which might become more important as the luminosity increases, such as winds, or bulk motion turbulence in the disc, as the data become *better* fit by our disc models as the luminosity approaches Eddington.

#### 4 DISCUSSION AND CONCLUSIONS

It has long been assumed that in the trans-Eddington luminosity regime two effects could become increasingly important for accretion disc models, (i) advection (Abramowicz et al. 1988; Mineshige et al. 2000) and/or (ii) outflows (Shakura & Sunyaev 1973; Poutanen et al. 2007; Ohsuga et al. 2009). In this paper we pin down the effect of advection by fitting ULX spectra with slim discs. We find that advection typically changes the best fitting spectral shape by removing photons in the intermediate energy range where the spectral peak is located and by releasing more photons at high energies (see in Figure 2b, upper panel). This is the characteristic signature of slim discs where photons are trapped in the accretion flow, accreted inward and released from inside the plunging

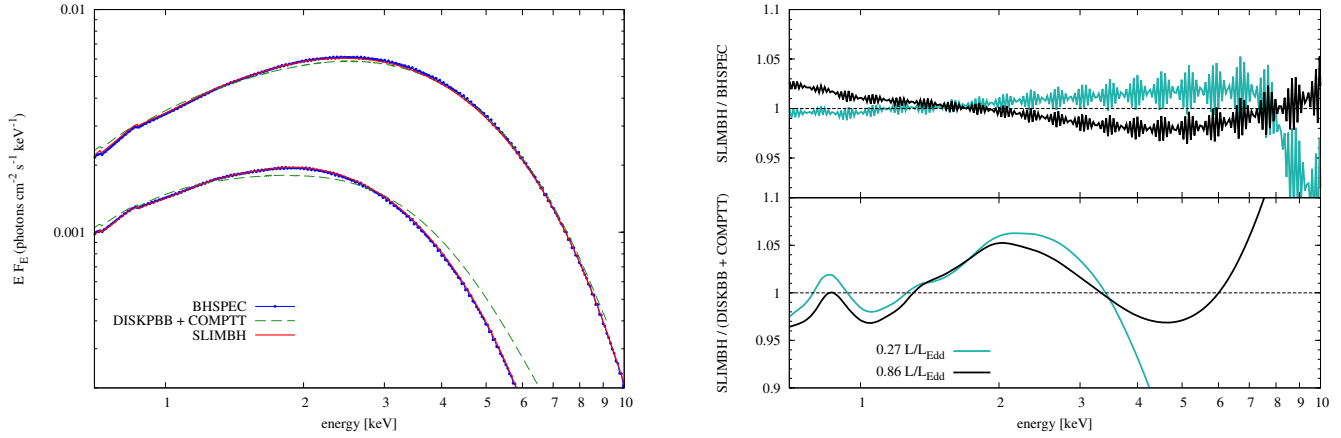
region (see Abramowicz et al. 2010, for a discussion of the inner edge of slim discs).

However, these changes make very little difference to the emitted spectrum for  $L < L_{Edd}$ , and we show here that this cannot be the reason for the mismatch between data and models seen in moderate luminosity ( $0.1 - 0.5L_{Edd}$ ) spectra from both this ULX and from galactic black hole binaries (Kolehmainen et al. 2011; Straub & Ghasemnezhad 2012). Real accretion discs at these moderate luminosities have a spectrum which is subtly broader than is currently expected from the best disc models. This additional broadening is most marked at lower mass accretion rates and gets weaker as the disc luminosity increases. This is exactly opposite to the luminosity behaviour expected from either winds, advection, bulk turbulence and/or inhomogeneities in the disc.

Instead, it could be connected to the (low level) coronal emission. We cannot constrain a weak high energy tail in our data, but this could potentially illuminate the disc and hence change the structure of the photosphere. However, we note that the most disc dominated GX339-4 spectrum in Kolehmainen et al. (2011), where the tail carries less than a few per cent of the total bolometric flux, shows this additional broadening. This is a very low level of illumination to cause a noticeable change in disc structure. Self-illumination of the inner disc by light-bending around the black hole may be a larger effect when the coronal emission is low (e.g., Miniutti & Fabian 2004). However, this should involve a constant fraction of the emission, rather than give a decreasing fraction as  $L/L_{Edd}$  increases.

Here we speculate that this may actually be a signature of magnetic pressure support in the disc. This will increase the scale height of the disc over and above that expected from a standard disc, so decreasing its density and hence its true absorption opacity. Electron scattering then becomes more important, broadening the spectrum (Davis et al. 2009). The extent of this change in disc structure depends on the ratio of magnetic pressure to total (radiation plus gas plus magnetic) pressure. This could explain the observed trend in the data if the magnetic pressure saturates to some fraction of the gas pressure rather than total pressure, as it would decrease in importance as  $L/L_{Edd}$  increases.

Other observations also strongly indicate that there is a change in behaviour in magnetic stress scaling between the gas pressure and radiation pressure dominated regimes. The rapid rise to outburst, which occurs (mostly) in the gas pressure domi-



**Figure 2.** *Left:* The SLIMBH (red) vs BHSPEC (blue) models for a high/low ( $0.86/0.27L_{\text{Edd}}$ ) luminosity disc. The black hole mass, spin and inclination are all tied at  $10M_{\odot}$ ,  $0.36$  and  $30^{\circ}$ , respectively. Advection makes little difference (less than a few percent) at even the highest luminosity considered here. Significant changes to the emitted spectrum due to advection are only seen at super-Eddington luminosities. The best fit phenomenological models to the data (green) show that the data are well described by the physical disc models at the highest luminosity, but are significantly broader at lower luminosity. *Right:* The corresponding model ratios SLIMBH vs BHSPEC (upper panel) and SLIMBH vs DISKPBB+POWERLAW (lower panel) for the same high/low (black/cyan) luminosity disc.

nated regime, requires very efficient transport of angular momentum as parametrised by a Shakura-Sunyaev  $\alpha$  viscosity of  $\sim 0.1$  (Dubus et al. 1999). However, if this efficient transport is maintained into the radiation pressure dominated regime then the disc becomes effectively optically thin, and its colour temperature correction increases markedly. This is in sharp contrast to the data, where the observed constancy of the colour temperature correction requires  $\alpha < 0.01$  at high  $L/L_{\text{Edd}}$ , where the disc is in the radiation pressure dominated regime (Done & Davis 2008; Straub et al. 2011). Thus the data from the ULX reported here, and previous work on the disc spectra seen from black hole binaries both support a change in magnetic stress scaling with total pressure. Current numerical simulations do not show this behaviour (Hirose et al. 2009), but these are at the limit of computational capabilities. Future research on how the self generated magnetic field from the MRI scales with pressure could resolve this issue.

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